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The Arcetri NEO Precovery Program

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Abstract. The Arcetri Near Earth Object Precovery Program (ANEOPP) is a project dedicated to the identification of images of Near Earth Objects (NEOs) on past archival materials, an activity usually referred to as *precovery*. Going years back in time to locate such images results in the acquisition of very good orbital information, which, in turn, allows astronomers to perform more accurate studies of the dynamical evolution and physical characterization of NEOs, as well as improve assessments of their impact hazard. We discuss the tasks involved in this work and the basic techniques used to yield successful identifications on photographic plates. Begun in mid-1999, ANEOPP has precovered more than 70 NEOs to date, which were previously observed only during the discovery apparition. The keys to obtaining these results have been: i) easy access to competitive collections both in digital form and as plastic copies; ii) traveling to additional collections; iii) the recent development of reliable algorithms to determine the boundaries of the recovery region, which is the portion of the celestial sphere where an asteroid with an uncertain orbit can be found at a given time.

Key words. minor planets asteroids – astrometry – celestial mechanics – astronomical data bases: miscellaneous – surveys

1. Introduction

In the last ten years discussions regarding searches for Near-Earth Objects (NEOs) have concentrated on the *hazard* aspect of these objects (Tedesco et al. 2000). In addition to theoretical studies, various publications have discussed the best methods to discover a significant fraction of the larger NEOs within a limited amount of time (Morrison 1992; Shoemaker 1995; Harris 1998). The goal of such a dedicated mid-term survey, the so-called *Spaceguard goal*, is to achieve 90% discovery of km-sized NEOs in about 10 years.

However, hazard mitigation requires much more than just discovery; above all, we need very good orbits for these bodies, and this can be achieved by obtaining astrometric positions over a long period of time. Orbital improvements are obtained both with follow-up observations immediately after discovery for the calculation of a reliable orbit and, subsequently, with recovery observations at other convenient apparitions years later.

Several professional observatories and a handful of good amateurs operating well-equipped stations take part in the process of follow-up astrometry of NEOs (Ticha et al. 2000). The amount of work required for this task is enormous; more efforts and resources are needed to follow them all properly. For this reason NEO coordination centers have been established recently (Boattini et al. 2000a; Hahn 2001; JPL-NEOP 2001). Here we describe an activity that complements the ongoing follow-up programs.

Recovery observations are a very important part of the process. There are generally four methods for obtaining astrometric data at a second apparition (Boattini & Forti 2000):

- direct recovery at the telescope at some future epoch;
- identification of the object with data already existing in the Minor Planet Center (MPC) files;
- accidental rediscovery of the object;
- direct recovery search on archival material (photographic or CCD).

This last type of recovery is called *precovery* (Steel et al. 1997). Various researchers have provided valid arguments to support precovery searches of NEOs in astronomical archives: i) it is the most rapid method for obtaining very good orbits soon after discovery; ii) it was aptly demonstrated in the last few years when two km-sized

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NEOs, 1997 XF_{11} and 1999 AN_{10}, were found to have very small collision probabilities with the Earth; the collision solutions could be excluded with data from photographic archives (Marsden 1998; Helin & Lawrence 1998; MPEC 1999-N21); iii) it saves a great deal of telescope time, as well as money; iv) it can be a day-time activity, unaffected by the vagaries of weather.

The Arcetri NEO Precovery Program, or ANEOPP, is a dedicated project started in mid-1999 by A. Boattini and G. Forti (Boattini et al. 2000b). At various stages other people became involved with this project: Roy Gal, Maura Tombelli, Luciano Tesi, Germano D'Abramo and Mike Read.

1.1. The new contribution of ANEOPP

As of April 9, 2001, over 1300 NEOs have been discovered, and their number is rapidly increasing. If we consider only the asteroidal component of the population (i.e. Near-Earth Asteroids, NEAs), accurate, multi-opposition orbits are available for about 490 NEAs. It is interesting to note that for almost 170 of these, data from a second apparition have been provided by photographic archival resources. Three-quarters of these precovery identifications have been made in the past two years alone.

If the initial orbit is very accurate, then precovery is generally a straightforward process because the object will be located at most a few arcminutes away from the nominal prediction. Various linear approximations can help observers locate the desired object under such conditions. These have been the conditions in which both 1997 XF_{11} and 1999 AN_{10} have been found. However, the recent theoretical studies which led to the identification of these potential impactors have recognized similar objects at smaller sizes, but with less certain orbits. This requires observing programs to improve their capabilities in order to recover these bodies when the sky uncertainty is much larger.

The search for NEAs with uncertain orbits is greatly complicated by nonlinear effects. The development of reliable algorithms to address these nonlinear effects is the result of dedicated studies started recently (Muinonen & Bowell 1993). A. Milani (1999), with various co-workers, produced a specialized software package, called Orbfit, to make such calculations (Appendix A). An online information service, the *Near Earth Object Dynamic Site, (NEODyS)*, is also available (Milani et al. 2000a).

ANEOPP makes use of these mathematical tools to guide precovery attempts of NEOs with poor orbits. Archives offer a very interesting opportunity to test search techniques for difficult recoveries without requiring a lot of telescope time. Although there is still a lot of work to be done, the first results, presented in this paper, are very encouraging.

This paper is organized as follows: after a short historical review of NEO precovery work so far, in Sect. 2 we describe the archives used by ANEOPP. In Sect. 3 we briefly review all the different steps that lead to a successful precovery identification. In Sect. 4 we discuss the methods used to search for NEAs and how we proceed when the the orbital information changes from case to case. By using the example of the Amor-type object 1998 NU, we show interesting aspects of the successful application of the multiple solution method. Finally, in Sect. 5 we summarize the results, consisting of the precovery of many NEOs, and provide general conclusions regarding the impact of this work on other aspects of NEO science.

1.2. Historical background on NEO precovery work

Precovery searches for minor bodies (comets and asteroids) are not a new activity, and have led to scientifically valuable results in the recent past. For example, the identification of the Amor-type object (4015) = 1979 VA with Periodic Comet Wilson-Harrington (1949 III) on a plate from 1949 (Bowell 1992), showed clear evidence that the distinction between asteroids and comets is not very straightforward. The well-known comet Hale-Bopp had its orbital solution significantly improved thanks to precovery data during the early stages of the follow-up process (McNaught 1995). The orbit of P/Swift-Tuttle was refined in the same way (Haver et al. 1992), after it had been secured by an accidental recovery (Marsden 1992).

After the pioneering efforts of the Anglo-Australian Near-Earth Asteroid Survey (AANEAS) in 1990–1996 (Steel et al. 1997), newly discovered NEOs are now routinely searched for on some photographic archives by a variety of dedicated programs. In addition to ANEOPP, significant efforts have been made by DANEOPS in Germany (Hahn et al. 1999) and by the team of E. Helin in California using the PCAS archive (Helin et al. 1979). An extensive precovery program for minor planets in general has also been carried out at Lowell Observatory using various archival collections. These initiatives have benefited from one obvious factor in common: access to some local archival resources. Part of their success is that they could conduct this activity without traveling around the world, because the working team either: a) owns the plate collection (PCAS and Lowell); b) is based where the plates have been taken and partly maintained (AANEAS); c) remotely retrieves archival material in a digital form on the internet (DANEOPS and ANEOPP).

2. Archives available for ANEOPP work: An overview

Currently, two main sources are available for ANEOPP activity: the Arcetri Plate Library and the Digital Sky Survey.

2.1. The Arcetri plate library

The Arcetri plate library consists of almost 5000 plate plastic copies (film copies), available from the following collections:

– The Palomar Observatory Sky Survey I (POSS-I);

- The Palomar Observatory Sky Survey II (POSS-II);
- The UKST southern sky survey, consisting in a set of J, equatorial J (EJ), selected short red (SR) and infrared (I) survey plate copies.

The film copies available at the library are part of a large project, whose goal was to map the entire sky in different colours, typically blue, red, and near-infrared. Three telescopes have been employed in this task: the 1.2-m Oschin Schmidt telescope at Palomar Observatory in the USA (Abell 1959; Reid et al. 1991); the 1.2-m UK Schmidt telescope in Australia and the 1.1-m ESO Schmidt telescope in Chile (Tritton 1983).

The plate library has been regularly accessed since February 2000. By using a hand magnifier we visually inspect the film copies in order to find the desired target. Minor planets can be efficiently discriminated from stars by their long trailed appearance; this is the result both of long exposures (35–100 min) and of the large plate scale of the 1.2-m Schmidt telescopes. Print copies of these surveys have been distributed all over the world and represent the most accessible resource for precovery work. In order to fully exploit their scientific potential, astronomers realized that photographs must be converted into a digital format, suitable for computer analysis. This led to the Digital Sky Survey, a project carried out at the Space Telescope Science Institute (STScI). Similar initiatives have been conducted at the US Naval Observatory (Levine 2000) and at the Royal Observatory at Edinburgh (ROE), *the SuperCOSMOS Sky Survey* (Read 1999).

2.2. The Digital Sky Survey

The Digital Sky Survey (DSS) was carried out in two phases: in DSS-I, plates were scanned at 25 micron resolution, corresponding to a 1.7″/pixel scale. The most recent surveys have been digitized with an image sampling of 15 microns, corresponding to about 1″/pixel scale (DSS II). This is approximately the intrinsic image resolution on the photographic plate emulsion (Bucciarelli 1999), so it is close to an ideal situation with little or no information loss.

There is a trade-off between the use of DSS and the film copies to locate precovery images: visual inspection of the film copies is the most time efficient way to look for the desired target since exploring a full Schmidt plate takes no more than half an hour. The field of view of these Schmidt plates is $6.4° \times 6.4°$. Covering the same area of sky using DSS images is much more time consuming because these images must be downloaded from the web: the largest, $30' \times 30'$ wide, are a few *MB* each in size. On the other hand, visual inspection of film copies has a disadvantage over DSS: it is fraught with physiological and subjective errors, and faint trails may pass undetected. Utilizing digitized images, one can extract information objectively and accurately.

3. Activity overview

The asteroidal component of NEOs has traditionally been divided into the Aten, Apollo and Amor classes (NEAs), based upon their current osculating orbital elements (Shoemaker et al. 1979). Comets have not been included in our program yet because the numerical tools we use can only solve the gravitational problem, and cannot be used if non-gravitational forces are also involved. However, we are currently undertaking tests to ascertain if such forces can be generally ignored. Hereafter, we apply our search methods and results only to NEAs.

The great bulk of the precovery work within ANEOPP has focused on NEAs observed only in the course of one opposition. Only bodies larger than 100 m are usually considered because of the low likelihood of recording smaller objects on the photographic emulsion. Our methodology is as follows:

- As soon as a preliminary orbit of a new NEA is available, we produce three separate sets of fully perturbed n-body ephemerides: 1949–1958, 1973–1987 and 1987–2000. These span all the appropriate epochs for the plate collections available;
- These ephemerides are cross-checked with the catalog files of the UKST, POSS I – II and ESO Schmidt archives, in order to identify possible useful plates. The result, a list of candidate plates, is available in different forms, depending on the expected sky uncertainty of the target and the amount of time we want to invest. This is a critical issue and is addressed in detail later;
- The third step is to separate the selected plates into two categories: first, those immediately available to us, either as plastic copies at the library and/or as part of DSS, and second, those plates that are available only in situ, where they were taken or are archived;
- Every reliable candidate, with motion vector and magnitude close to the predictions, is considered and measured using the USNO A2.0 astrometric catalogue (Monet et al. 1998);
- As soon as we have astrometric data for one or more candidates, we proceed to attempt an orbital linkage between the two sets of astrometric data (from two or more oppositions). If the linkage with the new data is successful, the cross-checking process is repeated in order to locate additional images of the object, with the advantage of a much smaller ephemeris uncertainty. After this step the data is finally submitted to the Minor Planet Center (MPC) if the attribution of the precovery images to the object we are searching for is virtually certain.

4. Search strategies and techniques

The problems that we need to analyze and solve are: i) the localization of the sky region where the object of interest may be found; ii) efficient coverage of this region; iii) limiting magnitude and trailing loss of the photographic system; iv) identification and correct attribution of the object.

4.1. Sky uncertainty: Representation and efficient coverage

The first step of the process is the calculation of the sky uncertainty in the position of the asteroid. Since this is a quite complex subject and is beyond the scope of this paper, we provide only a brief overview of the problem. For those who wish to know more about this topic, there are recent studies in the literature (Muinonen & Bowell 1993; Muinonen et al. 1997; Milani 1999; Milani et al. 2000b; Milani et al. 2000c).

In the classical approach, asteroid recovery was performed following a line in the sky, obtained by slightly varying the object's *mean anomaly, M*, for a given orbit. Although this is a good approximation when the sky uncertainty (*SU*) is small, this approach cannot be used with more difficult cases. Milani (1999) has developed increasingly complex algorithms to deal with cases with increasing difficulty. These algorithms have been implemented in a software package called Orbfit (Appendix A), which has been used in our precovery program.

4.1.1. Linear case

Each set of astrometric data, which is thought to belong to a specific object, contains a certain amount of error. From this data it is generally possible to calculate a preliminary orbit. It is also possible to represent the uncertainty of this orbit by a confidence region in the six-dimensional space of orbital elements. In order to derive the *SU* from this region, either a linear or a nonlinear theory can be used.

In the framework of the linear theory, the confidence region is approximated by a confidence ellipsoid, whose projection on the sky plane is an ellipse. Usually, this ellipsoid is elongated only in the direction of *M*, resulting in an ellipse that appears as a straight line segment. This segment, the long axis of the confidence region, is defined as the Line of Variation (*LOV*) (e.g., Milani et al. 1999).

Other times the *SU* has a more classic oval shape; under these circumstances search efforts become more time consuming since the search cannot be done only along one dimension.

The use of the linear theory, which is very efficient with small uncertainties, is not recommended when the confidence region becomes too large, because nonlinear effects can no longer be neglected.

4.1.2. Nonlinear theory

The use of a nonlinear theory is the appropriate method for addressing large sky uncertainties. Different sources of nonlinearity have been found: as we will see later, one apparent effect of nonlinearity is the projection of the confidence region on the sky plane. This region appears not as an ellipse, but rather a very asymmetric figure with respect to the object's nominal position.

When the *SU* is large, it often appears as a curved line segment, especially for objects observed only for a short arc and/or lost for a long time.

The nonlinear theory, which allows us to map all the points of the confidence region in the six-dimensional hypervolume, has the inconvenience of requiring heavy calculations. In order to reduce the amount of work, a semilinear theory has also been developed (Milani 1999).

This approach has two advantages. First, it approximates the boundaries of the confidence prediction region on the sky plane well enough in the great majority of cases; and second, it requires much less computational time, because it maps the confidence region only along a line, the longest axis of the confidence ellipsoid (the *LOV*).

We use the results of this semilinear theory in our search efforts, both when using Orbfit or the on-line version NEODyS. Our policy is to stop the search along the *LOV*, at the 3σ level, in order to make the search virtually complete.

4.1.3. Search windows and ensuing strategies

The second problem is finding the most efficient way to cover this region. We start with a tentative evaluation of the effort required to achieve a reasonable chance of success. Keeping in mind that there are no guarantees that precovery images will be found, our objective is to maximize the chances of locating the object while minimizing effort.

In order to obtain a list of plates where the target could be located, we need to define a *search window*. The search window (*SW)* is a square window of a size to be defined, which is always centered on the target's nominal position in the sky.

The cross-checking process defines the *SW* by comparing the position of the center of each plate from the catalogue with the nominal position of the target at the time the plate was exposed. If the angular distance between these two points in the sky is smaller than a certain number, which depends on the size of the Schmidt field of view (*SFOV*), then the object's position will be inside the *SFOV* and the target can be detected if it is brighter than a specific threshold magnitude. When a plate meets both requirements, we define it as a *candidate plate*. In order to be sure that no candidate plates are left undetected, the size of the *SW* must be at least as large as the *SFOV*. For each object we generate an *output file* listing all of its candidate plates.

Unfortunately, a complete search for such plates can be much more complex because there is always some uncertainty in the object position. Evaluation of the target's *SU* provides the full solution to this issue. We devise five scenarios which are based on the comparison between the object's *SU* and *SFOV*:

(A) - $SU \ll SFOV$
(B) - $SU < SFOV$
(C) - $SU \sim SFOV$

(D) - $SU > SFOV$
(E) - $SU \gg SFOV$.

In order to estimate the difficulty of a precovery search, we make a first guess, based on the uncertainty in the object orbit's semi-major axis.

The *SU* is smaller when plates have been taken closer to the discovery apparition and/or when the object is not near the Earth. The general trend is that uncertainties are larger when the object is brighter (i.e., closer to the Earth).

There is another trade-off: opportunities at fainter magnitudes, and therefore smaller uncertainties, can be unsafe because objects are frequently beyond the detection threshold of the plate.

As a matter of fact, the same object may experience more than one of the five scenarios during visibility opportunities at different epochs. Generally, (A) applies to bodies already numbered by the MPC or observed on multiple apparitions, (B) to single apparition objects with good orbits, while (C), (D) and (E) apply, respectively, to bodies with some *SU*, large *SU*, or to totally lost targets.

In the following subsections we discuss four tested procedures, ordered by level of increasing difficulty. The result of each procedure is to generate a different output file.

4.1.4. Nominal solution: Small window

If we are in case (A), i.e., with very good orbits, we consider a window slightly bigger than the *SFOV*: a $7° \times 7°$ window provides a safe margin to avoid missing plates. A larger window, such as $10° \times 10°$, is selected for cases (B) and (C): we define this as our *small window*. It is useful for targets that would not pose particular difficulties if the recovery had to be made at the telescope at some future epoch.

As soon as we have the full list of candidate plates, we select the ones with the smallest *SU* and start the search from them. The great majority of ANEOPP identifications were made using this *SW*.

4.1.5. Nominal solution: Medium window

If we are in case (C) or moving from (D) to (C), we need a larger window, such as $20° \times 20°$. However, the use of a square window is not appropriate because it will include in the output list plates which are far from the object's *LOV*. The solution we adopt is to consider a rectangular *medium window* of $20° \times 10°$, aligned along the direction of the *LOV*, provided in the ephemeris string of Orbfit.

This choice, often implemented at the plate library, resulted in some successul early precovery identifications: 2000 SY_2, 2000 LY_{27} and 2000 PM_8. When the discovery of the Aten-type object 2000 SY_2 was announced by the MPC (MPEC 2000-S36), this target had only 2 days' arc. Three hours later it was found only 6 degrees from the prediction on a plate taken in 1977. Probably, we would have missed that plate if we had used the *small window*.

2000 LY27 was located in a similar way, by relying on the data from the discovery announcement alone (MPEC 2000-M04).

2000 PM8, a 5-km Amor, was found on a UKST digitized plate without realizing that this trail had been already measured by AANEAS at the time the plate was exposed. The primary goal of AANEAS was to systematically search for new NEAs from the plates of the 1.2-m UK Schmidt Telescope as soon as they were taken. Unfortunately, in the particular case of 2000 PM8, then designated 1991 GM_{12}, the direction of motion for the trailed image was reported incorrectly, and targeted follow-up was not possible (MPEC 2000-Q23). Incoveniences like these could often occur when the techniques used for taking these plates were not optimized for asteroid detection.

A useful technique for solving this kind of problem is *exposure gating* (Helin & Dunbar 1990): by breaking the exposure into two parts of unequal duration on a single search plate, separated by a short blank interval, asteroids can be unambiguously discriminated from defects, and their motions, both apparent speed and direction, can be determined.

4.1.6. Nominal solution: Large window

As we move to objects with higher *SU*, we must expand the search window further. *Large windows*, such as $40° \times 10°$, can be successful in recovering such bodies. On the other hand, examination of the behaviour of the ephemeris uncertainty with time in Fig. 1 demonstrates how easy it is to lose some candidate plates when the *SU* undergoes intrinsic jumps that exceed the *SW*.

When the *SU* grows to tens of degrees, a fixed window centered on the nominal solution is not viable due to nonlinear effects. Other conditions also discourage the use of very large windows:

- The *LOV* can no longer be approximated by a straight line in the sky, and it often cannot be contained within a simple rectangular window, without the risk of including many unnecessary candidate plates;
- The identification of the desired object becomes very difficult. Although we can still find out where its *LOV* lies by using the NEODyS database, we no longer have reliable information about its angular speed and magnitude, two fundamental criteria for discrimination. In fact, they can both change significantly when we are not close to the nominal solution for geometrical reasons;
- Nonlinear effects also make it nearly impossible to combine the contributions to the coverage of the object's confidence region from multiple plates. Such calculations serve both to avoid duplication of effort and to find out which sections of the confidence region cannot be covered by the resources that are available from the output list.

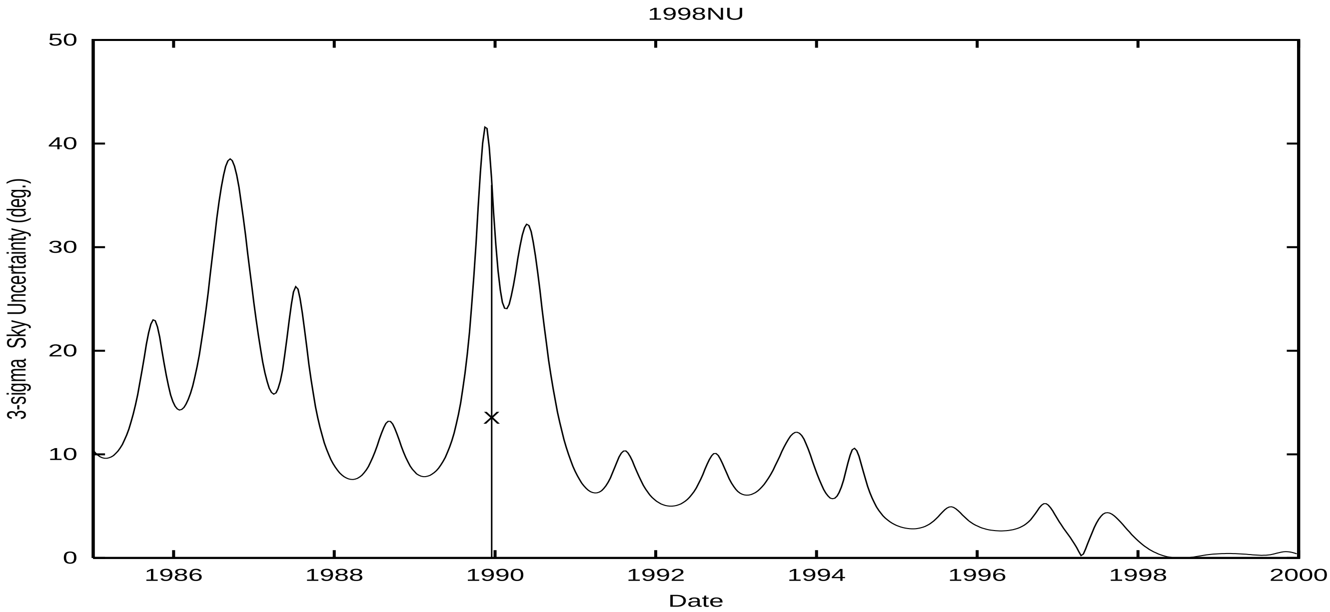

Fig. 1. This plot shows the sky uncertainty (*SU*) behaviour of 1998 NU between 1985 and 2000 using a linear approximation. At discovery, mid-1998, *SU* is less than $1''$, but it grows quite rapidly with time. The vertical solid line around 1990 is a projection of the semi-lenght of the line of variation (*LOV*) at the time of the precovery observation, stopped at the 3σ level. The crossmark shows the object position relative to the nominal solution, the X-axis of the plot.

4.1.7. Multiple solutions

When the target's orbital information is too poor for planning a search relying on a single orbit, we use another approach (Milani 1999; Milani et al. 2000b), wherein we sample the confidence region with a swarm of *virtual asteroids*, with a family of differing orbits, all compatible with the observations. Since the confidence region contains a continuum of orbits, each virtual asteroid is representative of a small region, due to its own orbital uncertainty, but to a much smaller degree.

Earlier, we approximated the confidence region in the sky along one dimension, described by the *LOV*. In this case each orbit is representative of a short segment of this one dimensional subset. This is the *multiple solutions* (*MS*) approach, which gives uniformly spaced (in σ units) solutions along the *LOV*. If n is the number of orbital solutions selected with the *MS* method, each corresponding to a *virtual asteroid*, then the cross-checking process is repeated n times, resulting in n output lists of candidate plates. By combining the contribution of all the candidate plates from these lists we can estimate our chances of finding one or more precovery images.

The most important requirement of the *MS* method is that these orbits must be very dense, otherwise we risk missing candidate plates. This can happen when the separation on the sky plane between two consecutive orbits is bigger than the *SW* we defined. For example, if a plate which happens to include the *LOV* of the target is located between the two orbits, it is very likely that it will not be reported in either of the output files, undermining the search effort.

A good indicator of this situation is when a plate is listed only for one solution, but not for any of the nearby orbits. In order to make sure that the number of orbits is dense enough, we also need to make an analysis of the *SU* during past close approaches for all these solutions. This is done by checking the full set of ephemerides of all the available orbits and analyzing the separation on the sky plane for each pair of nearby solutions. All of these elements help in devising the appropriate density of solutions for the confidence region.

The calculation of a great amount of orbits requires only a few minutes on a common CPU, but the human work analyzing the output files and searching the plates may be beyond our resources. For this reason, we prefer to start the search with fewer orbits and eventually repeat the search with a denser set if the object is not found. For each solution we tend to apply a $10° \times 10°$ *SW*. By exploring and analyzing each solution, it is possible to keep track of the ones that have been safely covered with archival material (*plate coverage*) and those that have not. When we use the *MS* approach, we usually get plate coverage only for some of the orbital solutions. Other orbits are not covered: the result is that the combination of covered and uncovered solutions follows an unpredictable pattern. Of course, there are many *intermediate cases*, where it becomes difficult to say if a specific orbit received plate coverage; for example, when the target is close to the plate limit and it is not clear what the true reason is for the missing detection.

The *MS* is a very powerful procedure because it takes into account some of the aspects of nonlinearity of the confidence region, such as the asymmetry in the *SU* (Fig. 3). It also avoids most of the inconveniences discussed in Sects. 4.1.5 and 4.1.6.

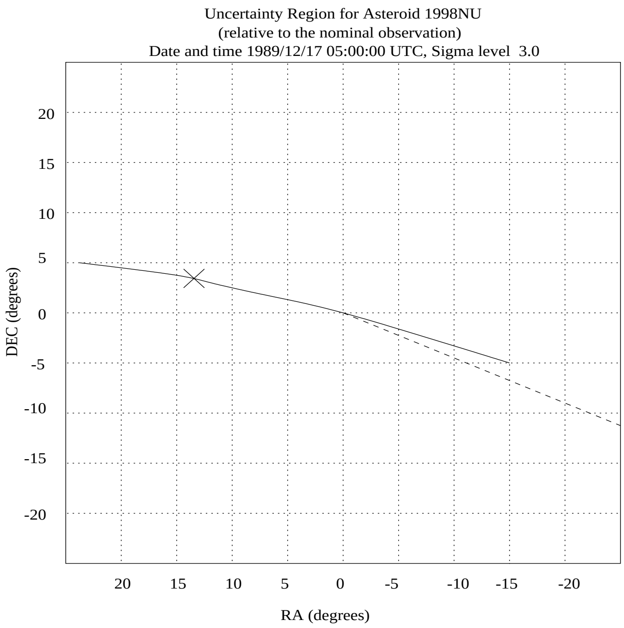

Fig. 2. Observing prediction for 1998 NU at the time of the precovery, as derived from the NEODyS database. The observing prediction shows the object *SU*, at the epoch the plate was exposed. The crossmark on the continous line (the line of variation) marks the object position on Dec. 17, 1989. It was found at about 14 degrees from the nominal position. The dashed line represents the direction of the object's motion vector on the sky, for the nominal solution.

Like the other methods, the search is started on plates with smaller *SU*. If the object is found, which often occurs on plates with small *SU*, it is worthwhile to repeat the search after the orbit has been improved. Occasionally this new check leads to the location of additional images on plates where the object's *SU* is significantly larger than on the plate where the first image was found.

If the object is not found, a denser set of orbits is produced in order to: i) locate additional candidate plates; ii) define more accurately which orbits received plate coverage. If the target still is not found during a check of all the available plates, then it is reasonable to take full advantage of these negative results: all the solutions from the densest set of orbits which do not have plate coverage can be inspected using a dedicated telescope at the earliest visibility opportunity. In case of a lost target, efforts can be eventually combined using a battery of telescopes looking at predictions with different orbits.

The first test of this method was implemented very recently, in the course of the independent precovery of 2000 QJ_1 (MPEC 2000-R02). A remarkable demonstration of the strength of *MS* was given with the precovery of the lost Amor 1998 NU, which we will discuss in Sect. 4.5.

4.2. Acquiring the astrometric data and securing attributions

When a good candidate is found, we must securely attribute this image to the NEA we are looking for (Milani et al. 2001). The policy of the Minor Planet Center for recoveries is, in general, to request observers for data on two different nights in order to provide a confident attribution. For precoveries, given the deep image scale of the large Schmidt telescopes and the often unusual angular speeds of these bodies, a single trail generally provides a safe margin for correct identification. For this reason, the astrometric procedure for the target consists of measuring the beginning and end of its trailed image using the USNO A2.0 catalogue. DSS images are particularly suitable for this purpose.

In any case the following general requirements must be satisfied for attribution:

i) the object must be located near its LOV;
ii) the predicted and measured angular rates and magnitudes must agree;
iii) the measured angular rates should allow the observer to discriminate it from objects belonging to more common orbital classes. If this is not the case, then a more accurate analysis is necessary, including either searching for other images at different apparitions, or making sure that its *SU* is very small in order to avoid confusion; this is especially true when trails are very faint. Most importantly, we repeat the search after improving the orbit (utilizing the location of the first precovery image) because the *SU* is reduced to a few arcsec, allowing us to discriminate very faint trails of real objects from ghost images.
If the object is bright, then it might be reasonable to assume that all the other objects of similar brightness are already known;
iv) the orbital linkage between the new data (which provides the starting orbit) and the old data must be successful;
v) finally, we may chose not to release our precovery data or the MPC may chose to hold it until there is an opportunity to re-observe the target at the telescope for confirmation of the tentative candidate.

4.3. Limiting magnitude and the trailing loss effect

An additional aspect of the precovery work is the evaluation of the potential of a photographic system in terms of limiting magnitude and its degradation due to the target's angular rate. In Table 1 we report approximate limiting magnitudes for each color of two sky surveys, POSS-II and UKST. These limits are for stellar objects in good seeing ($<1.5''$) and can vary by up to ± 0.4 magnitude from plate to plate. Unfortunately the performance for minor planets is much lower, because these deep limiting magnitudes were achieved with long exposures. Even slow moving main-belt objects (MBOs) leave distinctive trails: the longer the trails, the less deep the limiting magnitude will be. This loss is called *trailing loss*.

Harris (1994) provided the background and formalism allowing the comparison of asteroid detection efficiencies for different photographic and CCD systems. Steel (1995) used these results to measure the asteroid discovery efficiencies for telescope systems at Siding

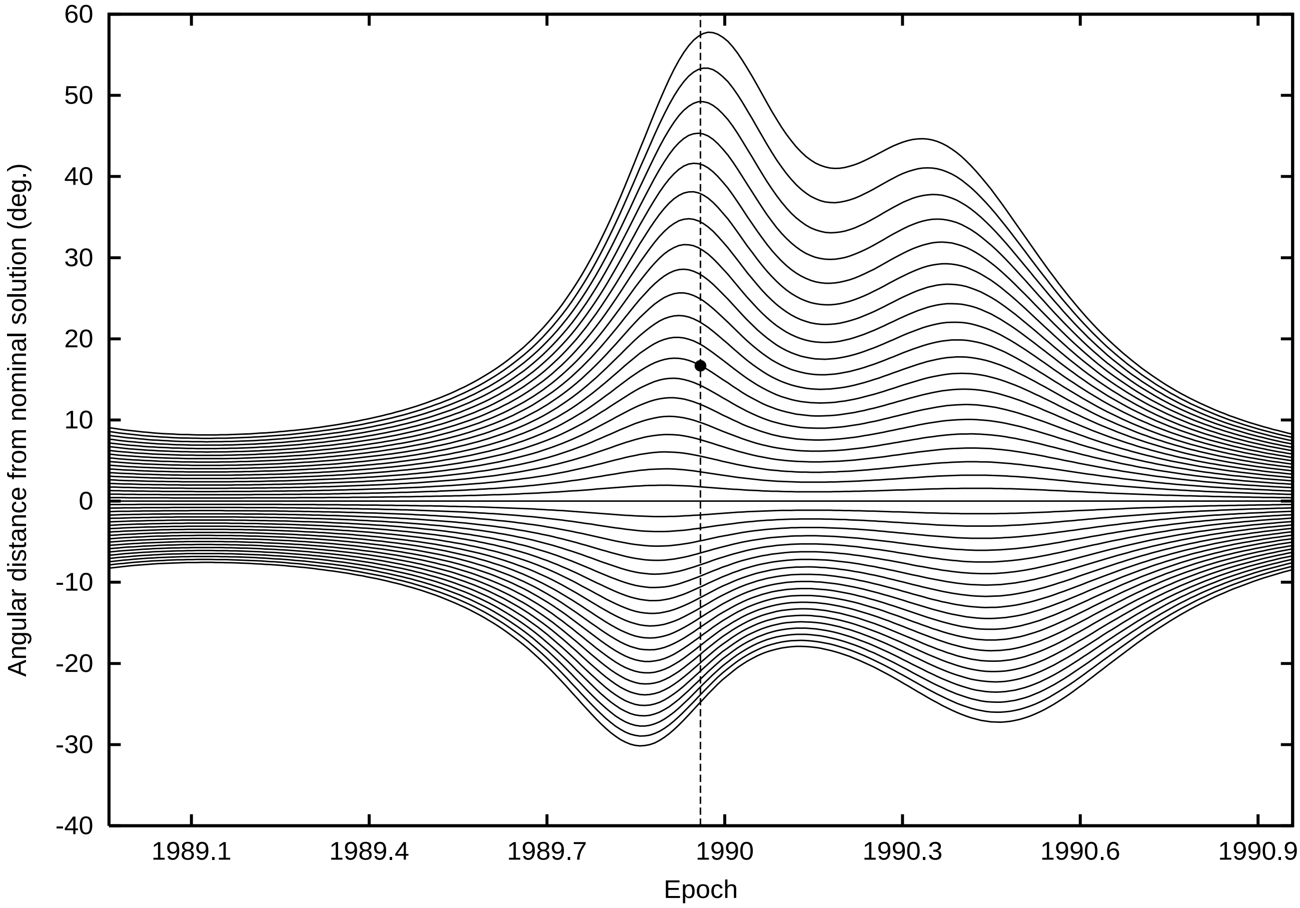

Fig. 3. Precovery circumstances of 1998 NU. In this plot we can see 41 continuous curves, each one corresponding to one of 41 orbits produced with the *MS* method at the 3σ level. For all of them the plot shows the angular distance from the nominal solution, which is represented by the only curve perfectly parallel to the X-axis. In this scheme the nominal solution is the orbit No. 21, while the confidence region is filled with 20 orbits on each side of the nominal solution. The position of 1998 NU is indicated by the small dot in the middle of the plot: it is located very close to solution No. 29. The *MS* figure covers two years, from 1989 to 1991. It is important to notice its asymmetric shape, an evident manifestation of nonlinearity.

Spring Observatory. Their treatment of a photographic system is based on three equations, each applicable to a different range of angular speeds:

Pseudo-stationary images: $r \leq (A^{\frac{1}{2}}/t)$

$$m_{\rm lim} = m_0 + 1.25 \log_{10}\left(\frac{D^2 t}{A}\right). \quad (1)$$

Short-trailed images: $(A^{\frac{1}{2}}/t) < r \leq (l/t)$

$$m_{\rm lim} = m_0 + 1.25 \log_{10}\left(\frac{D^2}{rA^{\frac{1}{2}}}\right). \quad (2)$$

Long-trailed images: $r > (l/t)$

$$m_{\rm lim} = m_0 + 1.25 \log_{10}\left(\frac{D^2 l}{A^{\frac{1}{2}} r^2 t}\right) \quad (3)$$

where $m_{\rm lim}$ is the limiting magnitude of the system, m_0 is a constant (evaluated from demonstrated performance of a system of known characteristics), D is the effective telescope aperture in metres (allowing for obscurations by the secondary mirror and support, plate holder, reflectivity losses, vignetting, etc.), t is the exposure time (s), A is the image area (arcsec^2), r is the angular speed in the sky plane (arcsec s^{-1}) and l is the correlation length (arcsec) defined as $l = 10 \times 2(A/\pi)^{\frac{1}{2}}$ for photographic systems. An application of these calculations is described in the next paragraph.

Table 1. Limiting magnitudes for POSS-II and UKST surveys. These limits are for stellar objects in good seeing and can vary by up to ±0.4 magnitude from plate to plate.

Survey col.	Emuls.	Filter	POSS-II	UKST
$B_{\rm j}$(lim)	IIIa-J	GG395	22.5	22.5
$R_{\rm c}$(lim)	IIIa-F	OG590	20.8	21.5
$I_{\rm c}$(lim)	IV-N	RG715	19.5	19.5

4.4. The example of 1998 NU

A good application of the techniques discussed in this section led to the precovery of the lost asteroid 1998 NU, an Amor with an estimated size of 2–3 km. It was discovered by the Spacewatch program as a $20.5-21.0V$ target on July 2, 1998. Additional observations provided an arc of 27 days, leading to the computation of a preliminary orbit which was not good enough to allow an easy recovery. Since this was a relatively large NEA, we set up a precovery plan. The extent and the behaviour of the object *SU* with time, shown in Fig. 1, suggested that we had to use the *MS* approach. By running the *fitobs* routine of the Orbfit software, we produced a total of 41 orbits, each one compatible with the observations at the 3σ level. For each of these orbits we derived a list of candidate plates. A review of the plate listings showed that: i) there was a nice opportunity in 1989 from POSS-II plates, and ii) searches at previous apparitions required a denser set of orbits.

The 41 solutions turned out to be sufficient for success: in fact, 1998 NU was located on the POSS-II plate SF02992, which was taken on Dec. 17, 1989. Figure 2 shows the object *SU* at the time of the precovery. The new improved orbit is almost coincident with the orbital solution No. 29, as we can see from Table 2 and Fig. 3, where nonlinear effects are quite remarkable. Table 2 is a reproduction of the plate output list produced by the *MS* method.

The new orbit allowed the MPC to identify some unlinked observations from 1999 (MPEC 2000-R57). After we located an additional image from POSS-I in 1953, the MPC assigned a permanent number to this object (18736).

Another interesting feature of this detection analysis is shown in Fig. 4, where we plot the angular speed of 1998 NU versus its visual magnitude for all 41 solutions at the precovery date. Using the procedure described in Sect. 4.3 we calculated the detection efficiency of the POSS-II red plate SF02992 for a moving object, plotting it with a dashed line. As Table 1 shows, red plates do not have the same performance as the blue plates, but they still approach magnitude 21. The threshold limit for this red plate was derived by using information from the POSS-II catalog and by assuming or calculating the value of additional parameters: $m_0 = 17.4$, $A = 8$, $l = 32$, $D = 1$ and $t = 4200$. The threshold is not very rigid and we should allow at least a ± 0.5 magnitude variation to account for asteroid and plate variation. For this plate we use Eq. (1) for $r \leq 2.5$ arcsec hour^{-1}, Eq. (2) for $2.5 < r \leq 27.4$ arcsec hour^{-1}, Eq. (3) for $r > 27.4$ arcsec hour^{-1}.

We can look at this plot in another way: if a hypothetical search for 1998 NU had to be carried out on that night covering the whole confidence region with a set of red plates identical to SF02992, we are virtually certain that 1998 NU would have been detected. The only problem would have been how to discriminate it from MBOs because about half of the orbital solutions produce slow angular rates.

4.5. An unusual case: 2000 BF_{19}

2000 BF_{19} is an Apollo of 500 meters in size, which was discovered by the Spacewatch program on January 28, 2000. It came to the attention of the astronomical community during the early stages of the follow-up process because it was found to have a very remote chance of collision with the Earth in the near future. Further observations excluded this possibility and facilitated the identification of a precovery image (MPEC 2000-D13). The good plate (from POSS-II) was exposed on October 4, 1991, with 2000 BF_{19} at magnitude 18. As can be seen from Fig. 5, this case is quite different from 1998 NU (Fig. 2). The confidence region does not appear as a line segment because the uncertainty in M was not dominant over that of other orbital elements. On that date the object could be located anywhere on a large portion of the plate and not simply along a thin line (the *LOV*). To secure the identification, we had to pay particular attention to the angular speed expected from each position on the sky plane of the plate.

4.6. Work on virtual impactors

There is another area where archives can provide a precious contribution. In Sect. 4.1.4 we introduced the notion of *virtual asteroids* in order to address the problem of targets with very poor orbits. If one of these virtual asteroids is on a collision path to the Earth, we define it as a *virtual impactor, (VI)* (Milani et al. 2000c).

The condition of being on a collision path strongly constrains the orbital elements, and the region of sky to explore becomes relatively small. This makes dedicated observing campaigns for negative observations possible, in the hope of not finding the target at the expected position. In this way we can exclude the object being on a collision course without investing a great deal of effort in a difficult search.

2000 PN_9 is the first object investigated in these terms, before it was located on two POSS-II plates, confirming that it will not pose any danger in the foreseeable future (MPEC 2000-Q37). A search plan for other *VIs* was carried out for another NEA, 1998 OX_4, which is still lost. About 200 meters in size, this is currently the biggest known NEA with non-zero collision probabilities with the Earth (Milani et al. 2000c).

5. Results and statistics

5.1. Single opposition NEAs

ANEOPP has been quite successful in locating new object prediscovery images on archival plates quickly after their discovery. The most relevant results are summarized in Table 3. It reports a list of 80 NEAs, arranged in chronological order and divided into four sets, depending on the

Table 2. Output sample of multiple solutions for 1998 NU: three consecutive solutions (Nos. 28–30) are listed, showing the successful identification from POSS-II red plate SF02992. Variation of angular speed (arcsec/hour) and apparent magnitude are already evident among these solutions. The position angle of the *LOV*, expressed in degrees, is counted from North to East. 1998 NU was found very close to solution No. 29 as can be seen from the astrometric positions at the bottom: they are reported in the MPC 80-character format.

Plate number, epoch and coordinates	Orbital solution	Object position RA	Dec.	Mag.	Angular speed - RA/Dec arcsec/hour		Direction of *L.O.V*
SF02992	28	03 38 31.08	+24 05 01.9	17.8	−50.9	−19.6	77.6
1989 12 17.20000	29	03 49 02.11	+24 37 04.8	17.7	−53.1	−19.1	78.6
03 42 24 +25 07.6	30	04 00 11.76	+25 08 00.6	17.6	−55.0	−18.3	79.6

```
J98N00U 2 1989 12 17.17569 03 47 56.83 +24 35 03.0          17.5 V      261
J98N00U 2 1989 12 17.22431 03 47 52.85 +24 34 43.7                      261
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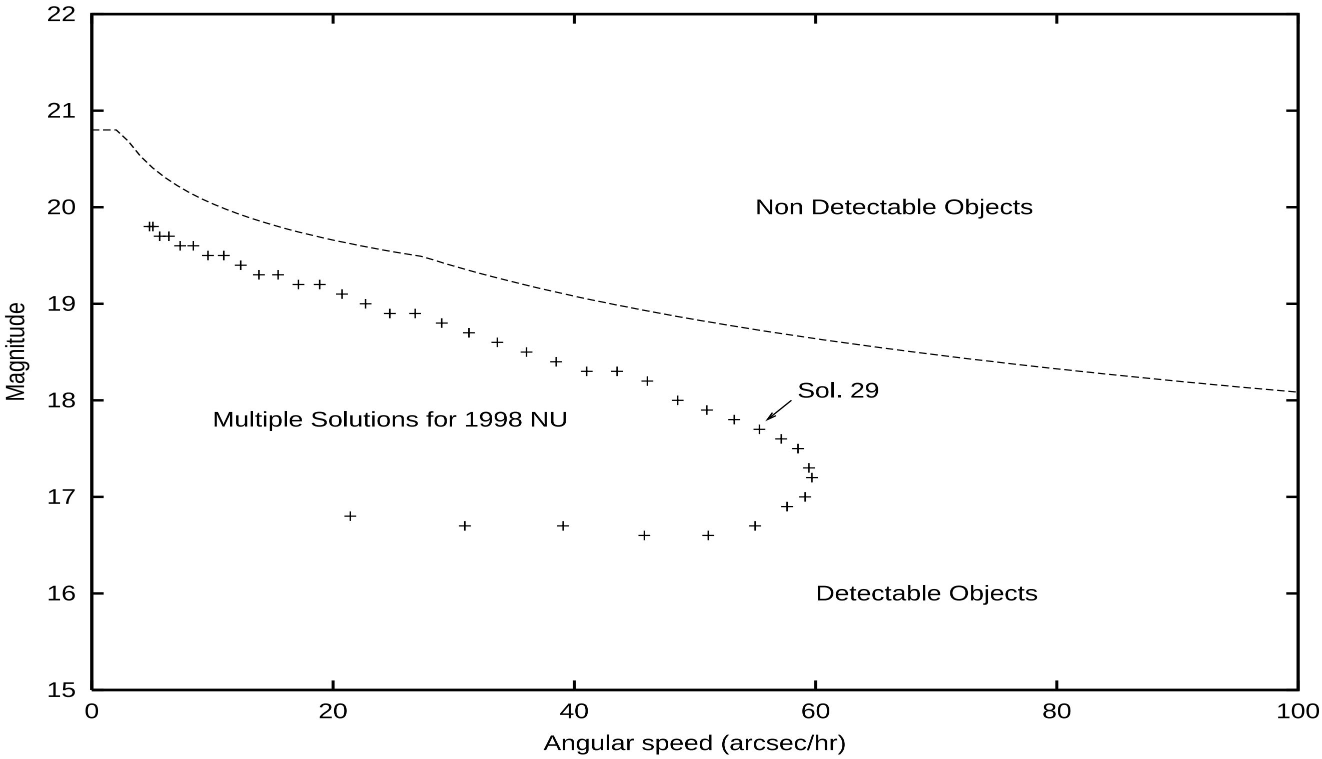

Fig. 4. This plot shows apparent motion versus visual magnitude for all 41 orbital solutions considered in the search for 1998 NU. The dashed curved line is the detection limit of the POSS-II red plate SF02992, derived by using appropriate values for the variables used that appear in Eqs. (1–3).

survey in which they were first located. These objects were single opposition at the time of the precovery, and became multi-opposition targets following these identifications. All have been published in Minor Planet Electronic Circulars (MPECs).

The first column reports identifications found directly from POSS-I. They have been less numerous because: i) this survey does not go as faint as the others; ii) sky coverage is reduced especially by the fact that blue and red plates were taken consecutively; iii) NEAs tend to show higher uncertainties, because POSS-I was created about 50 years ago; and iv) we could not benefit from the print copies of POSS-I, because of their poor quality.

The second column lists precoveries from POSS-II, a project carried out from 1985 to 1999. We found 24 NEAs on this collection and this is an interesting result that gives considerable credit to the quality of this archival material. In fact, POSS-II plates were already inspected by Palomar personnel while grading the survey plates: as a by-product of this work they discovered many supernovae, comets and 16 NEAs. Additionally, a collaboration with the California Institute of Technology allowed us to

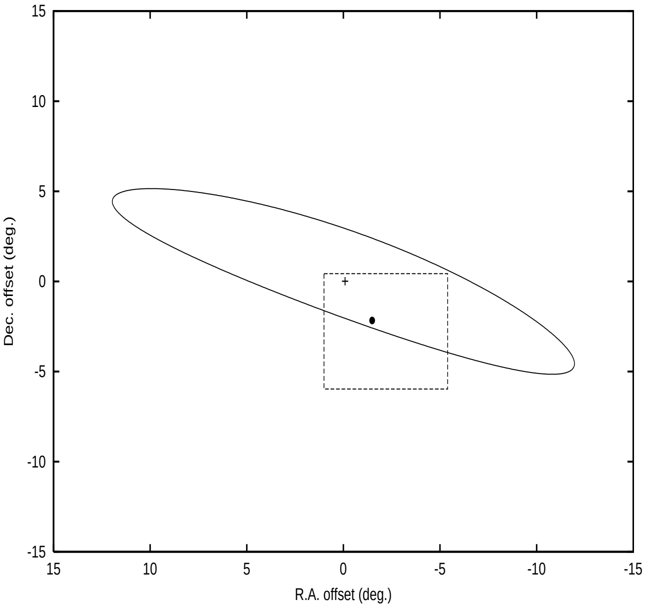

Fig. 5. Observing prediction for 2000 BF$_{19}$ at the precovery epoch, on Oct. 4, 1991. Unlike 1998 NU, its sky uncertainty (SU) has a more classic elliptical shape. The small cross symbol indicates the centre of this figure (the nominal solution). Both the cross symbol and the object position (the circular dot) are located inside the POSS-II red plate SF04256, the square figure on the sky plane.

access some of the digitized material before it was publicly available. This material is part of the Digital Palomar Sky Survey (DPOSS), a collaboration between Caltech, STScI and other Institutes, in which the entire POSS-II has been digitized and represents part of DSS. The goal of DPOSS is to catalog all objects on the entire Northern Sky (Djorgovski et al. 1998).

The third column of Table 3, reports identifications from a set of plates of the UKST collection which was started in 1973. It includes material also available in digitized form. More than 20 objects were found. The great majority of these were measured from images taken before 1990, because the AANEAS program had not started yet. AANEAS discovered 38 NEAs in seven years of activity (Steel et al. 1997).

Most of the identifications of ANEOPP from these first three lists have been obtained directly from DSS, while the Arcetri plate library has been used for bodies with more uncertain orbits.

The last column lists NEAs found from another set of the UKST collection which is not remotely accessible through the web. In order to produce these results, one of us (A.B.) arranged a two week visit to the Royal Observatory of Edinburgh (ROE), where the great bulk of the UKST archive (∼17 000 plates) is maintained. The goal of the visit was to systematically search for all of the known NEAs observed in the course of one opposition, leaving some spare time for multi-opposition targets.

Thanks to the excellent support from ROE staff coordinated by Mike Read, 300 plates were inspected. This resulted in the precovery of 22 objects, including the lost Amor 1992 BL$_2$. Considerable efforts were made to look for additional lost objects, but there was not enough time to perform a complete search of all the candidate plates for each target.

The work on the plates at ROE continues thanks to the direct collaboration of Mike Read, who very recently contributed to the identifications of the last four objects in this column.

Table 3. This table reports a listing of single opposition Aten, Apollo and Amor asteroids (i.e., NEAs) precovered by ANEOPP, arranged in chronological order of precovery. It comprises 80 objects, whose identifications have been published in the Minor Planet Electronic Circulars: 74 NEAs were directly precovered by ANEOPP; 4 are independent detections (found by other teams hours before) and have been reported in parenthesis; 1999 RM$_{28}$ (!) was located and measured by R. H. McNaught at Siding Spring, based on the ANEOPP prediction; 1998 MR$_{24}$ (!!) was independently identified from pre-existing observations by M. E. Sansaturio and G. Forti. Targets found with the *MS* method are underlined. Precovered NEAs have been divided into four sets, depending on the archival collection where they have been located first.

POSS–I	POSS–II	UKSTU (survey)	UKSTU (non survey)
1999 GJ$_4$*	1998 MX$_5$	1996 BZ$_3$	1999 RM$_{28}$!
1999 YT	1997 WT$_{22}$	1999 LF$_6$	1998 MR$_{24}$!!
1999 UM$_3$	1997 GH$_3$	1998 FM$_5$	1998 YB$_8$
2000 CQ$_{101}$	1999 HZ$_1$	2000 CN$_{101}$	1999 JU$_3$
2000 ED$_{104}$	2000 BF$_{19}$	1999 VM$_{40}$	2000 JS$_{66}$
1998 WT	1998 QH$_2$	1999 RH$_{33}$	1998 WM
	1999 WC$_2$	(2000 ES$_{70}$)	1999 KX$_4$
	1999 XA$_{143}$	2000 BO$_{28}$	1999 RR$_{28}$
	1999 RD$_{32}$	2000 GQ$_{146}$	2000 QP
	2000 DH$_8$	2000 GC$_2$	1998 OR$_2$
	2000 GP$_{82}$	2000 GR$_{146}$	2000 EZ$_{148}$
	2000 DV$_{110}$	2000 HO$_{14}$	1998 UT$_{18}$
	2000 PN$_9$	2000 JQ$_{66}$	1998 BX$_7$
	(2000 QJ$_1$)	2000 HA$_{24}$**	1999 GJ$_2$
	2000 NG$_{11}$	2000 HD$_{24}$	1992 BL$_2$
	1998 NU	2000 CG$_{59}$	1999 YB
	2000 GV$_{147}$	2000 LY$_{27}$	2000 NF$_{11}$
	2000 UV$_{13}$	2000 JN$_{10}$	1999 JV$_3$
	2000 UT$_{16}$	2000 PM$_8$	1999 LQ$_{28}$
	2000 VM$_2$	2000 SY$_2$	1999 RP$_{36}$
	(2000 YK$_{29}$)	2000 SE45	2000 JT$_{66}$
	(2000 YJ$_{66}$)	2000 VN$_2$	2000 PG$_5$
	2001 BW$_{15}$		2000 UV$_{16}$
	2001 AU$_{43}$		2000 WP$_{148}$
			2000 XK$_{44}$
			2001 CV$_{26}$

Additional notes:
∗) 1999 GJ$_4$ was found in the course of a joint effort with a team led by Ted Bowell at the Lowell Observatory in Arizona;
∗∗) 2000 HA$_{24}$ was independently located by E. Helin and K. Lawrence on 1993 photos from the PCAS archive.

Table 4. The left column lists NEAs precovered during their discovery apparition (so = same opposition); the middle column reports NEAs already observed at multiple oppositions (mo); the right column lists a few objects belonging to other unusual classes.

NEAs – so	NEAs – mo	Unusual Objects
1988 PA	1950 DA	1996 TE_{11}
1989 VB	1991 VE	1998 XB_9
1991 TB_2	1996 AS_1	1999 US_3
1992 BC*	1997 WS_{22}	(10199) Chariklo
1992 SZ	1997 XF_{11}	
1994 NE	1998 EP_8	
1997 YM_3	2000 NF_5	
	(02212)	
	2000 OG**	

Additional notes:
*) It was located thanks to a collaboration with S. Levine of the US Naval Observatory.
**) Independent identification.

5.2. Other precoveries

Some time has been invested in searching for NEA images on plates taken during their discovery apparition, in order to extend their observing arc. A list of such targets is reported in Table 4, in the left column.

Occasionally we have located and measured multi-opposition NEAs, but it is not a priority of this project, since there are a growing number of teams that can contribute when precovery work becomes easier (Table 4, middle column).

Very little time has been devoted to other unusual populations. The most important of these identifications is that of the Centaur-type object (10199) Chariklo. Chariklo, previously designated as 1997 CU_{26}, is a 200-km sized object and, with (2060) Chiron, is the biggest known body in the Jupiter-Neptune region (*the Centaur region*). It moves along an almost circular orbit, located between Saturn and Uranus. Using data from three oppositions, 1997, 1998 and early 1999, it was located on two POSS-II film copies, one from 1988 and the second from 1989. The new very accurate orbit has also been used to obtain stellar occultation candidates for 1999–2005 (Stone et al. 2000).

Another minor segment of our activities is the identification of precovery images of MBOs. Being a very time consuming activity, this work has been limited to those targets discovered by a few Italian observatories, where some of the authors have been involved for some time. The main output of this initiative is to speed up the process of having these bodies numbered by the MPC. As a result Asiago Observatory at Cima Ekar (MPC code 098) and San Marcello Pistoiese (104) became two of the most prolific discovery sites in Italy for numbered objects.

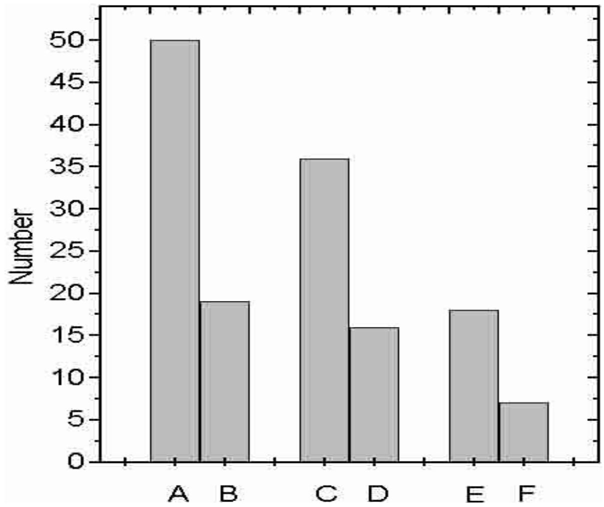

Fig. 6. NEAs are categorized into three pairs of bins, based on an analysis of their motion rates at the precovery epoch: (A) is the cumulative representation of NEAs that could be discriminated by other minor planet populations: (B), the shorter bin of the pair, reports targets that are too faint for detection in the course of a general survey. In the same way (C) and (D) report bodies that could mimic specific minor planet populations, such as Mars-Crossers and high-inclination asteroids, like the Hungaria class. (E) and (F) list all the cases where angular rates are completely indistinguishable from MBO motions.

5.3. Motion rates of precovered NEAs

One interesting result of this work is a preliminary analysis of the angular speeds of the precovered targets at the plate epochs. The objective is to compare the fraction of NEAs that could have been discovered by a dedicated search program using the precovery resources as search material, with the total number of precoveries.

Using software similar to the one first developed in the course of the Spacewatch program (Scotti et al. 1991; Rabinowitz 1991; Scotti 1994), we perform this analysis by dividing angular rates of precovered objects into three categories.

- When NEAs are not too far from Earth, they generally show apparent angular speeds that cannot be reproduced by any other minor planet class: either they move too fast and/or at unusual angles with respect to the ecliptic. We call these *virtually secure NEAs*, since they can be immediately discriminated by the observer;
- A second case is when bodies from other orbital classes, like Hungarias, Mars-crossers or high inclination/eccentricity groups can display similar rates. We call these *suspected NEAs*;
- Other times the geometric circumstances and/or their larger geocentric distances make them indistinguishable from classical MBOs. We call these *disguised NEAs*.

Results of this investigation are shown in Fig. 6: three pairs of bins are represented, each one related to one of the categories defined above. From a total of 104 precovery images, we find 50 virtually secure NEAs, 36 suspected NEAs and 18 disguised NEAs. Of these, 19, 16, and 7 NEAs, respectively, cannot be found by a dedicated program, principally because of the faintness of the trail, based on our personal experience developed with minor planet photographic searching.

From these numbers we find that only in 31 out of 104 cases would NEA discoveries have been virtually secure, ∼30% of the total. Of course, if time for follow-up is allocated, some NEAs of the second group could reveal their true nature, pushing the total number to about 40% or more. Unfortunately, past NEO photographic programs have been conducted under significant time pressure, which worked against the accomplishment of proper discrimination and follow-up coverage of the slower candidates. Another factor that keeps this percentage fairly small is the trailing loss, because it produces a bias that increases the relative number of detections with slower rates. Furthermore, many survey plates were not taken close to the opposition region where confusion among asteroid classes is minimal.

The results shown in Fig. 6 are valid only for large Schmidt telescopes because of their large area and deep limiting magnitude. Thanks to the plate scale of these instruments, it is easier for the observer to use the apparent length of a trail as a first discriminating factor, before the acquisition of astrometric data refines the first guess.

5.4. Size distribution of precovered NEAs

Among the objects listed in Table 3, 69 were discovered between 1998 and 2000. An interesting aspect of the precovery work is the comparison between the size distribution of NEAs discovered during 1998–2000 (Fig. 7a) with that of the 69 Atens, Apollos, Amors precovered by ANEOPP (Fig. 7b) which were discovered within the same time span.

The comparison of the features of these two size distributions gives an insight into the potential of these photographic surveys. The size scale is expressed in absolute magnitude (H): we used the data from the Minor Planet Center database. The conversion between H and diameter depends on the asteroid's intrinsic reflectivity (albedo), which is often unknown. Although NEO albedoes can vary by a full order of magnitude (Bowell et al. 1989), as a rule of thumb, $H = 16.0$ corresponds to objects with diameter between 2 and 4 km, while $H = 18.5$ to asteroids between 0.5 and 1.2 km (MPC, H – diameter conversion).

Examining Fig. 7b, the small number of precovered NEAs brighter than $H = 16.0$ can be explained by the fact that most of them are already known, either by observations during multiple apparitions or holding permanent numbers assigned by the MPC.

For $H > 16.0$ there is a steep rise in the number of precovered targets. This means that current NEO search efforts are discovering many objects in this size range, also

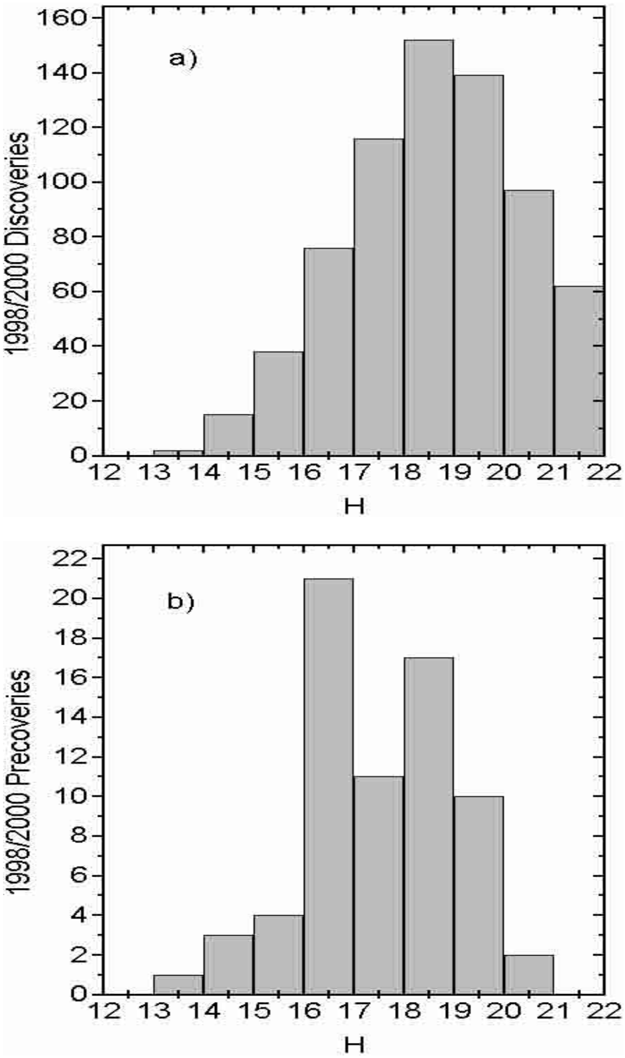

Fig. 7. Histogram **a)** shows the size distribution in absolute magnitude (H) of all NEAs discovered in three years, from 1998 to 2000. Histogram **b)** shows the size distribution of the 69 single-opposition Atens, Apollos, Amors (NEAs) precovered by ANEOPP and discovered between 1998–2000; a concentration of objects between $H = 16.0$ and $H = 19.5$ is quite evident, although some random fluctuations are present.

indicating that the inventory within the same range is not close to being complete.

In Fig. 7b, the cut-off at faint magnitudes is also quite steep. This is likely due both to the relative small rate of discovery in the magnitude range 21–22 and the less frequent opportunities to record them accidentally on photographic plates. The future availability of CCD archival resources will very likely increase the relative fraction of objects precovered at smaller sizes.

5.5. Further remarks

The number of precovery identifications made in the course of the ANEOPP project is the consequence of two main factors:

a) Increased efficiency in the NEO discovery rate by a few NASA funded NEO survey programs, with the

LINEAR project taking a leading role in the field (Stokes et al. 2000). Each month there are a few new NEOs that can be searched for in archives with reasonable expectations of success. Part of the credit goes to numerous stations that provide immediate follow-up observations.

b) Significant improvements in the field of orbital computations and general database access, including both the development of new services and the improvement of those already existing: i) DSS provides an immense set of data in the form of digitized images; ii) the MPC releases new astrometric data for NEAs on a daily basis in the form of Daily Orbit Update (DOU) MPECs; iii) Orbfit demonstrably provides reliable information for the calculation of the sky uncertainty and for searching for bodies with poor orbits.

Other services have been very helpful from time to time, in particular some of those developed at Lowell Observatory (Koehn & Bowell 1999), with the *Select List of Orbital Parameters, (SLOP)* being the most useful.

6. Future developments of astronomical archives for NEO work

We have presented a general overview of the activities of the Arcetri NEO Precovery Program, and discussed in more detail search techniques and preliminary results. Archival collections taken with the biggest Schmidt telescopes have been the most successful resources for the identification of NEO trails. Such resources are only a small fraction of the estimated two million plates/films worldwide from professional archives and an unknown number from private collections; ANEOPP and other teams are working to obtain access to additional archives soon.

Unfortunately, a significant part of this historic material is not accessible to the scientific community. Hudec (1999) describes a vicious cycle in which the lack of users becomes the predominant problem. The astronomical plate archives mostly suffer from a lack of suitable instrumentation for extracting scientific data from the plates. Part of the problem is limited or no search software. There are, however, very encouraging signals; in fact, very important work in this direction has been made by Tsvetkov et al. within IAU Commission 9, Working Group on WF Imaging, with their list/catalogue (although not yet complete) of wide-field plate archives (Tsvetkov et al. 1998). The related Wide-Field Plate Database (WFPDB) was installed at CDS in Strasbourg (Bonnarel et al. 1999). A coordination center has also been established at Uccle Observatory, known as the *UDAPAC* project.

As our inventory of km-sized NEAs becomes more and more complete, there will be fewer and fewer opportunities to find precovery images of newly discovered NEAs. Nevertheless, since these and smaller bodies approach the Earth at a different distance during each encounter, their magnitude varies dramatically from encounter to encounter. This means that there might be many smaller objects, yet to be discovered, whose images are contained in existing photographic archives. So, in years to come, when virtually all km-sizes objects have been identified, they may still offer numerous images of the smaller bodies.

Another important resource for the future is represented by CCD archives. Current NEO survey programs already offer an invaluable source for future precovery work because they sweep huge regions of the celestial sphere each month with powerful state of the art CCD systems. Since NEOs are discovered by means of automatic detection software, it is not unusual to have missing detections even at relatively high signal-to-noise ratios, as recently demonstrated by the recent case of 2000 SG_{344}. Targeted image processing of this data can also produce additional identifications. For these reasons it is highly recommended that these programs maintain such archives, something that unfortunately does not always occur.

Acknowledgements. The DSS are copyrighted material. See their proper acknowledgements.

In addition, we thank and acknowledge all the observers who took the original plates included in this project.

We also want to thank all the people that helped us during the early stages of this program. Particular thanks go to the team led by Dr. Andrea Milani of the University of Pisa for developing most of the software that led to the success of this project, to the Arcetri Observatory for giving us access to the plate library and to Dr. Giovanni Valsecchi and Dr. Andrea Milani for providing useful comments to improve the manuscript.

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Appendix A: Efficient orbit computation

All the observing predictions and part of the orbital determination and linkages reported in this paper have been performed with the Orbfit software package (ver. 2.0). Orbfit has been developed by a consortium formed in 1996 by the groups led by A. Milani (Univ. of Pisa), by M. Carpino (Obs. Milan/Brera), K. Muinonen (Univ. Helsinki), Z. Knezevic (Obs. Belgrade) and G. B. Valsecchi (IAS-CNR, Rome). This software package is distributed as free software (under a GNU type public licence) and can be obtained either by anonymous ftp or by contacting any one of the observers.

References

Abell, G. O. 1959, Astron. Soci. Pac. Leafl., 8, 121

Boattini, A., D'Abramo, G., & Valsecchi, G. B. 2000a, The Spaceguard Central Node, `http://spaceguard.ias.rm.cnr.it/SSystem/SSystem`

Boattini, A., Forti, G., Gal, R., & D'Abramo, G. 2000b, The Arcetri NEO Precovery Program, `http://www.arcetri.astro.it/science/aneopp/`

Boattini, A., & Forti G. 2000, P&SS, 48, 939

Bonnarel, F., Fernique, P., Louys, M., & Bienayme, O. 1999, in Treasure-Hunting in Astronomical Plate Archives, Proc. of the International Workshop held at Sonneberg Observatory, March 4 to 6, 1999, 235

Bowell, E., Hapke, B., Domingue, D., et al. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews, 524
Bowell, E., IAU Circ., 5585 and 5586
Bowell, E. 1997, Hierarchical Astrometric Observing: Rules of Thumb, unpublished
Bucciarelli, B. 1999, in Treasure-Hunting in Astronomical Plate Archives, Proc. of the International Workshop held at Sonneberg Observatory, March 4 to 6, 1999, 45
Carpino, M., Milani. A., & Chesley, S. R. 2001, in preparation
Djorgovski, S. G., Gal, R. R., Odewahn, S. C., et al. 1998, Wide Field Surveys in Cosmology, 14th IAP meeting held May 26–30, 1998, Paris (Publisher: Éditions Frontières), ISBN: 2-8 6332-241-9, 89
Hahn, G., Doppler, A., & Gnadig, A. 1999, The DANEOPS project, http://earn.dlr.de/daneops/
Hahn, G. 2001, The Near-Earth Asteroids Data Base, http://earn.dlr.de/nea/database.htm
Harris, A. W. 1994, in Seventy-Five Years of Hirayama Asteroid Families, ed. Y. Kozai, R. P. Binzel, & T. Hirayama, Astron. Soc. Pacific Conf. Ser., 63, 203
Harris, A. W. 1998, P&SS, 46, 283
Haver, R., Boattini, A., Tombelli, M., & Kohoutek, L. 1992, IAU Circ., 5670
Helin, E. F., & Shoemaker, E. M. 1979, Icarus, 40, 321
Helin, E. F., & Dunbar, S. R. 1990, Vistas Astron., 33, 21
Helin, E. F., & Lawrence, K. 1998, IAU Circ., 6839
Hudec, R. 1999, in Treasure-Hunting in Astronomical Plate Archives, Proc. of the International Workshop held at Sonneberg Observatory, March 4 to 6, 1999, 28
Koehn, B., & Bowell, E. 1999, Asteroid Observing Services, http://asteroid.lowell.edu
Levine, S. 2000, http://www.nofs.navy.mil/data/FchPix/cfra.html
Marsden, B. G. 1992, IAU Circ., 5620
Marsden, B. G. 1998, IAU Circ., 6837
McNaught, R. H. 1995, IAU Circ., 6198
Milani, A. 1999, Icarus, 137, 269
Milani, A., Chesley, S. R., & Valsecchi, G. 1999, A&A, 346, L65
Milani, A., Chesley, S. R., & Ronci, N. 2000a, Near Earth Object Dynamic Site, http://newton.dm.unipi.it/neodys/
Milani, A., Chesley, S. R., & Valsecchi, G. B. 2000b, PSS, 48, 945
Milani, A., Chesley, S. R., Boattini, A., & Valsecchi G. B. 2000c, Icarus, 145, 12
Milani, A., Sansaturio, M. E., & Chesley, S. R. 2001, submitted to Icarus
Minor Planet Center, Conversion of Absolute Magnitude to Diameter, http://cfa-www.harvard.edu/iau/lists/Sizes.html
Minor Planet Center, 2000, MPEC, 1999-N21
Minor Planet Center, 2000, MPEC, 2000-D13
Minor Planet Center, 2000, MPEC, 2000-J47
Minor Planet Center, 2000, MPEC, 2000-M04
Minor Planet Center, 2000, MPEC, 2000-Q23
Minor Planet Center, 2000, MPEC, 2000-Q37
Minor Planet Center, 2000, MPEC, 2000-R02
Minor Planet Center, 2000, MPEC, 2000-R57
Minor Planet Center, 2000, MPEC, 2000-S36
Monet, D., Bird, A., Canzian, B., et al. http://xena.harvard.edu/software/catalogs/ua2.html
Morrison, D. (ed.) 1992, The Spaceguard Survey, Report of the NASA International Near-Earth-Objects Detection Workshop, Jet Propulsion Laboratory, Pasadena, http://impact.arc.nasa.gov/reports/spaceguard/
Muinonen, K., & Bowell, E. 1993, Icarus, 104, 255
Muinonen, K., Milani, A., & Bowell, E. 1997, in Dynamics and Astrometry of Natural and Artificial Celestial Bodies, ed. I. Wytrzyszczak, J. H. Lieske, & R.A. Feldman (Kluwer Academic, Dordrecht), 191
NASA-JPL Near-Earth Object Program, 2001, http://neo.jpl.nasa.gov
Rabinowitz, D. 1991, AJ, 104(4), 1518
Read, M., The SuperCOSMOS Sky Survey 1999, http://www-wfau.roe.ac.uk/sss/
Reid, I. N., Brewer, C., Brucato, R. J., et al. 1991, PASP, 103, 661
Scotti, J. V., Gehrels, T., Rabinowitz, D. L., Asteroids, Comet, Meteors, 1991, 541
Scotti, J. V., A. Milani, et al. (eds.) 1993, Asteroid, Comet, Meteors, 17
Shoemaker, E. M., Williams, J. G., Helin, E. F., & Wolfe, R. F. 1979, in Asteroids, ed. T. Gehrels, 253
Shoemaker, E. M. (Chairmain) 1995, Report of the Near-Earth Object Survey Working Group, NASA, Solar System Exploration Division, Office of Space Science, Washington, DC 20546-0001, June 1995
Space Telescope Science Institute, The Digital Sky Survey http://stdatu.stsci.edu/dss/
Steel, D. I. 1995, Publ. Astron. Soc. Aust., 12, 202
Steel, D. I., McNaught R. H., Garradd, G. J., Asher D. J., & Russell, K. S. 1997, Austr. J. Astron., 7, 67
Stokes, G. H., Evans J. B., Viggh, H. E. M., Shelly, F. C., & Pearce, E. C. 2000, Icarus, 148, 21
Stone, R. C., McDonald, S. W., Elliot, J. L., & Bowell, E. 2000, AJ, 119, 2018
Tedesco, E. F., Muinonen, K., & Price, S. D. 2000, P&SS, 48, 801
Ticha, J., Tichy, M., & Moravec, Z. 2000, P&SS, 48, 787
Tritton, S. 1983, The UKSTU Handbook
Tsvetkov, M., & Tsvetokova, K. 1999, in Treasure-Hunting in Astronomical Plate Archives, Proc. of the International Workshop held at Sonneberg Observatory, March 4 to 6, 88